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Severe convection nowcasting in the Alpine region: the COALITION approach

L. Nisi, P. Ambrosetti, L. Clementi

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Abstract

COALITION (**Co**ntext and Sc**al**e Or**i**ented **T**hunderstorm Sate**lli**te Predict**o**rs Developme**n**t) is an innovative object-oriented model developed in the context of the EUMETSAT Fellowship program. The main purpose of this project is to increase the lead time in nowcasting severe convection over complex terrain. Data provided by different sources (e.g. Meteosat Second Generation Rapid Scan, Weather Radar, Numerical Weather Prediction and climatology) are merged into a heuristic model. Furthermore, the orographic forcing (often neglected in heuristic nowcasting models) is considered and included in the system as an additional convection triggering mechanism. This is particularly important over areas characterized by complex terrain like the Alps.

The COALITION algorithm merges evolving thunderstorm properties with selected predictors. The storm evolution is the result of the interaction between convective signatures (objects) and their surrounding environment. Eight different “object-environment” interactions are described in eight modules, providing ensemble forecast of thunderstorm attributes (satellite- and radar-based) for the next 60 minutes. The different ensemble forecasts are then summarized into one single map to facilitate user’s interpretation. COALITION provides with a frequency of five minutes the probability that a detected convective cell develops into a severe thunderstorm. It aims at being used as an auxiliary information for taking important decisions about severe storm warnings.

The first version of COALITION is fully automatic and has been tested on 80 convective cells randomly selected from a database: a preliminary validation shows useful probability of detection (POD) and an acceptable false alarm rate (FAR) for lead-times until 20 minutes before the thunderstorm reaches the severe stage. The system is going to be tested in real-time during summer 2012.

Table of Contents

1 Introduction

During the warm season, intense thunderstorms regularly affect the Alpine area. Such high impact, convective phenomena can produce local flash floods, strong wind gusts and hail causing considerable damages. It is estimated that in Switzerland, 50-80% of all weather-related losses are usually caused by severe thunderstorms. The need to increase the lead time in nowcasting severe convection is well-acknowledged. Numerical weather prediction models provide satisfactory forecasts on regional to global scales, but have difficulties in predicting the exact time and location of smaller scale phenomena like thunderstorms. Current heuristic methods, such as those based on satellite and radar imagery, rely on output post-processing, satellite nowcasting products (e.g. SAF, MPEF) or neuronal methods. Besides, existing radar-based schemes are well suitable for detecting and extrapolating thunderstorms. The detection of convective features in its early stage still remains a difficult task, especially over a complex terrain like the Alps. Information characterizing the storm environment, in particular retrieved by satellites, is very useful to detect convective structures even in the early stage and to predict its further development (Koenig and De Coning, 2009; Setvák et al., 2003; Rosenfeld et al., 2008).

This document reports on the achievements made over the last three years in the context of the EUMETSAT Fellowship project at MeteoSwiss. The research Fellowship started on May 15th, 2009 and it ended on May 14th, 2012.

The first year was devoted to several preparation tasks, like the investigation of current operational nowcasting methods, convection predictors, the development of the COALITION methodology and the setup of a dedicated case-study database. The second year was dedicated to the theoretical and numerical development of the core algorithm and the coding part. First modules were implemented producing the first qualitative results. In the third and last year some more modules have been implemented taking advantage of additional data. Furthermore, a first complete version of the system has been developed, tested and validated with a large number of thunderstorm cases.

The system has been designed for a real-time use. Some further improvements and additions were implemented during the last months of the project. It is expected to test COALITION in real-time during the convective season of 2012. The feedbacks from the forecasters will be collected in order to proceed with a second tuning-phase during autumn 2012.

This report includes all information related to the COALITION project and presents all its achievements, structured in different sections. After a presentation of the objectives of the project, two sections are devoted to the description of the database and the input data. The main section widely describes the COALITION methodology. Results and a preliminary validation follow, together with a discussion and an outlook. At the end of the document, information about the dissemination (publications, presentations) as well as relevant references are provided.

2 Objectives

The goal of COALITION is to provide early identification of potential severe thunderstorms in terms of intensity and location, through the rapid modeling of the available predictors. Thunderstorms are driven by processes which range from the synoptic to the microphysical scale (Doswell, 2001; Kottmeier et al. 2008; Rosenfeld and Woodley, 2000). COALITION extracts and merges information provided by a variety of sources such as meteorological satellites (Meteosat Second Generation Rapid Scan Service MSG RSS), weather radars (MeteoSwiss radar network), Numerical Weather Prediction (COSMO model), Digital Elevation Models (DEM) and climatological analysis. The orographic forcing is very important in the alpine area, where mountain ridges and valleys considerably affect a thunderstorm process throughout its entire life-cycle (triggering, reactivation, and decaying) (Barthlott et al., 2005; Kottmeier et al. 2008; Davolio et al., 2010, Huntrieser et al., 1996).
The challenge of the project was to construct an innovative methodology aimed at merging physical and heuristic information into a single model. The output is the probability for a detected object (i.e. a convective cell) to develop into a severe thunderstorm; the output is updated with a frequency of five minutes. This probabilistic product will support end-users (weather forecasters) in the decision process for issuing severe storm warnings. As demonstrated in the EUMETSAT Convection Working Group 2012 workshop, the user community is very interested in new methods aiming to improve accuracy and increasing lead time of severe weather warnings. One of the basic goals is to understand end-users' needs providing them reliable, easy-to-use, high-quality information.

3 Cases selection and database

For the development, tuning, and validation of the algorithm a sizeable database has been set-up. About seventy stormy days, including more than 300 single convective cells (cases) ranging from weak to severe have been selected. The case selection even includes a few non-convective cases. This extended case selection is needed for an exhaustive assessment of POD and FAR of the COALITION model (see *Section 6.2*).
The cases have been grouped according to synoptic conditions (derived from NWP analysis), cells intensity and duration provided by a radar based nowcasting algorithm called "Thunderstorm Radar Tracking" TRT (Hering et al., 2004). TRT detects, classifies and tracks convective cells according to a dynamic threshold scheme (based on maximum reflectivity (dBZ), vertically integrated liquid content (VIL) and the height of the 45 dBZ echo top). An extrapolation of the cell position for the next 60 minutes is computed and a graphical output is overlaid on a geographical map. The output of this system is also used as an independent dataset for cross validation purposes (see *Chapter 6*).
Extra-tropical thunderstorms are classified into three main groups, namely pre-frontal, frontal, and stationary storms. For the first two groups, which are characterized at synoptic scale by the presence of important temperature gradients and strong wind shears, orography plays a secondary role. On the other hand, topography is very important in case of stationary thunderstorms, where synoptic-scale pressure gradient are weak and hence solar heating dominates. According to this characterization, the whole set of convective days was stratified into the following five groups:

1. Severe, long-living cells (usually prefrontal convection ahead of cold fronts)
2. Mixed situations (several thunderstorms at the same time over a wide area, typically in case of an incoming cold front)
3. Localized mixed situations (stationary thunderstorm cells, weak wind)
4. Weak convective activity
5. Possible ambiguous situations (strong stratiform and/or orographic precipitations).

For each convective day, several products from different sources were stored in the database:

- Meteosat Second Generation L1.5 products
- Meteosat Second Generation MPEF products (Cloud Mask, Cloud Top Height, Regional Instability Index)
- SATCAST Convection Initiation product (Mecikalski et al. 2006, 2008, 2010a and 2010b, Siewert et al. 2010)
- Nowcasting SAF Cloud Top Height (PGE03) and Rapid Developing Thunderstorm (PGE11)
- Radar based Thunderstorm Radar Tracking products
- Radar based Vertical Integrated Liquid content
- Radar precipitation products
- NWP: ECMWF, COSMO2-CH and COSMO7-CH products

4 Input data

Figure 1 shows all the products ingested into the algorithm every five minutes. All products are operationally available in the COALITION database and are preprocessed in order to be used by the COALITION algorithm. Table 1 summarizes additional information for each product, like sensor type and operational available frequency. The description of the data merging scheme is provided in *Chapter 5*.

Origin	Acronym	Name	Operational frequency (min)
Satellite (MSG-MPEF)	CTT	Cloud Top Temperature	5
Satellite (MSG-Nowcasting SAF)	CTH	Cloud Top Height	5
Satellite (MSG-Nowcasting SAF)	RDT	Rapid Developing Thunderstorms	5
Satellite (MSG-Nowcasting SAF)	CI	Convection Initiation	5
Radar (Swiss Radar Network)	VIL	Vertical Integrated Liquid	2.5
NWP (COSMO-2 Switzerland)	CAPE	Convective Available Potential Energy	180
Lightning (Meteorage)	LI	Lightning Climatology	(static)
Digital Elevation Model	DGRAD	Directional Gradients	(static)

Table 1: Origin, acronyms, short description and available operational frequency (at MeteoSwiss) for the data ingested by COALITION.

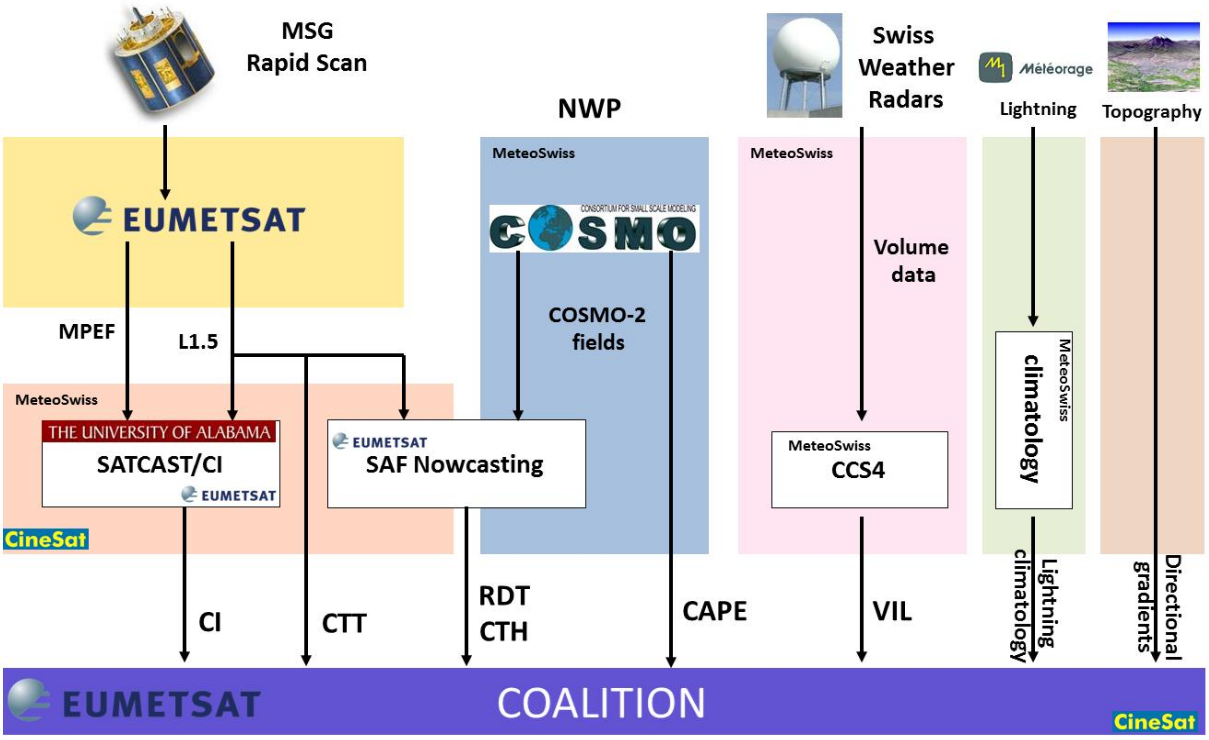


Figure 1. COALITION input data ingested in the current version. See table 1 for acronyms description and product list.

5 COALITION methodology

5.1 Overview

COALITION is a newly developed nowcasting approach to forecast severe convective storms by assimilating data provided by different sources and combining them by means of a conceptual model.

The algorithm models severe convection predictors (parameters describing the environment) and evolving thunderstorm attributes as interacting elements. The core of the algorithm works as an engine that links the convective characteristics (attributes) of an object (e.g. cloud top temperature, vertical integrated liquid) with the surrounding environment described in terms of CAPE, convection initiation, etc.

In COALITION, the object “convective cell” is selected using the satellite product cloud top temperature (CTT) and on the radar product vertically integrated liquid water content (VIL). The object is confined using both CTT and VIL products. For CTT, the object confinement is provided by an external algorithm (SAF Nowcasting Rapid Developing Thunderstorms), while for VIL the object is generated by ad-hoc confinement rules (thresholding).

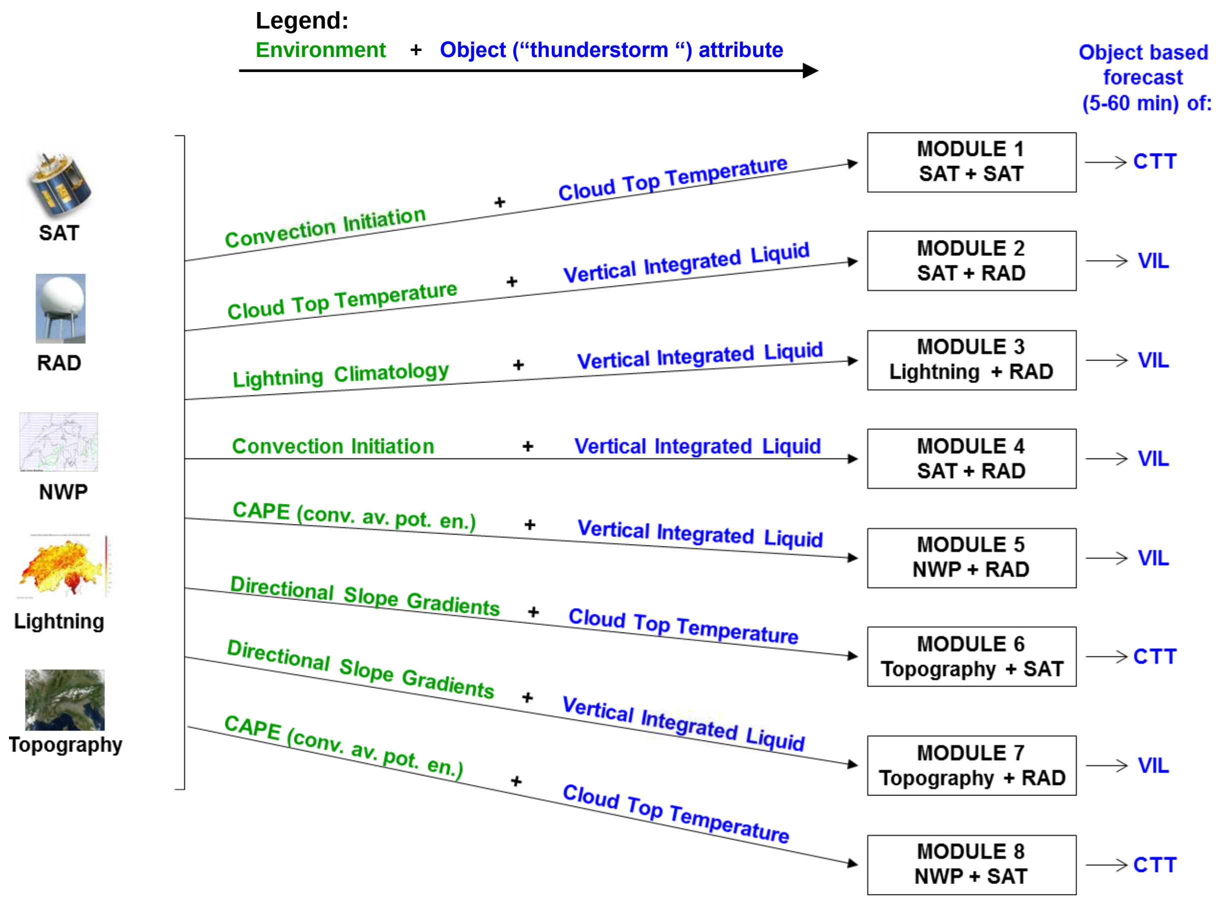


Figure 2. The eight modules implemented in the current version of COALITION. Products used as external environment are in green, objects in blue.

Several environmental parameters are described as gridded fields which can be retrieved from available observation sources. For COALITION, only the environments which have well-known physical or heuristic correlations with the object attributes have been selected. The current version of the model includes eight different “object-environment” couples, defined following semi-empirical rules based on forecaster’s experience and simple conceptual models, which are applied as functionals (momentum or energy) in the model.

Figure 2 shows the eight implemented modules. Three modules provide three different ensemble forecasts for the parameter CTT; the remaining five modules provide the same, but for VIL. In the actual version of COALITION, if CTT is not available, the algorithm does not run, since the basic product used in COALITION (RDT) is created based on CTT data. In case of missing VIL data, a reduced version of the algorithm (including three modules only) can still be run.

Table 2 depicts the semi-empirical rules that motivated the “object-environment” pairs selection. Each module provides a sixty-minute ensemble forecast for the corresponding object attribute.

MODULE	Data combination	Semi empirical rules
1	Evolution of the CTT based on the environment defined in terms of the Convection Initiation product	Stronger Convection Initiation signal of a convective cell → more updraft is available for its cloud top cooling (towering of the cloud)
2	Evolution of the VIL based on the environment defined in terms of CTT	Faster cooling of the cloud top of a convective cell → more energy is available for increasing its VIL
3	Evolution of the VIL based on the environment defined in terms of a lightning climatology	Higher density of cloud to ground lightning over a specific area → more energy is available for increasing the VIL of a convective cell developing in this area
4	Evolution of the VIL based on the environment defined in terms of the Convection Initiation product	Stronger Convection Initiation signal of a convective cell → more energy is available for increasing its VIL
5	Evolution of the VIL based on the environment defined in terms of the Convective Available Potential Energy (CAPE)	Higher instability values → more energy is available for increasing the VIL of a convective cell developing in this area
6	Evolution of the CTT based on the environment defined in terms of orographic information (slope gradients)	A convective cell is moving toward a mountain (orographic forcing) → more updraft is available for its cloud top cooling (towering of the cloud)
7	Evolution of the VIL based on the environment defined in terms of orographic information (slope gradients)	A convective cell is moving toward a mountain (orographic forcing) → more energy is available for increasing its VIL
8	Evolution of the CTT based on the environment defined in terms of the Convective Available Potential Energy (CAPE)	Higher instability values → more updraft is available for its cloud top cooling (towering of the cloud)

Table 2. In this table the eight modules and semi-empirical rules used to select product pairs are described.

5.2 Algorithm theoretical description and numerics

The COALITION methodology borrows the approach from the physics of general dynamic systems. As illustrated in *Figure 3* the interaction of the object with the surrounding environment (e.g. forcing), is modeled as a particle-field interacting system. The dynamics of a particle moving within a potential field is commonly described by the Hamilton's equations.

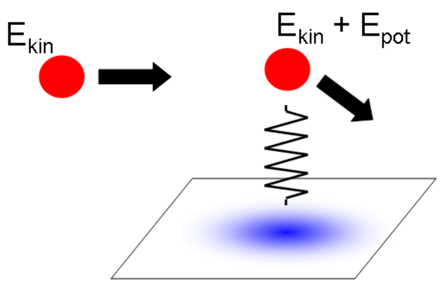


Figure 3. Simple illustration of the COALITION model. The object-based approach makes use of the energy conservation principle from the physical mechanics. The forecast of object attributes is the result of the solution of Hamilton's equation (eq. 5.2.1).

Forecasts provided by different implemented modules correspond to the evolution of the object attributes provided by the solution of Hamilton's equations. The Hamiltonian function for a time-independent system is given by

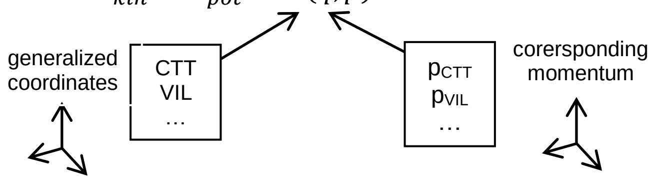
$$H(\vec{q},\vec{p}) = H(q_1 \cdots q_n, p_1 \cdots p_n) = E_{tot} \qquad (5.2.1)$$

where $q_1..q_n$ is the set of generalized coordinates representing the observed object attributes (e.g. CTT, VIL) and $p_1..p_n$ are the corresponding generalized momenta. The Hamilton's equations are:

$$\dot{\vec{q}} = \partial H/\partial \vec{p} \qquad \dot{\vec{p}} = -\partial H/\partial \vec{q} \qquad (5.2.2)$$

The COALITION algorithm scheme is based on an energy conservation assumption (i.e. without dissipation). The involved potential is built-up by using the characteristics of the external environment, whereas the computation of the pseudo-kinetic component is based on the rate-of-change in time of attributes describing the convective cells (objects). Regarding the energies implied in this model, we use the word "pseudo" for distinguishing model energies derived by information combination from true physical energies (e.g related to movements or to thermodynamics).

$$E_{kin} + E_{pot} = H(\vec{q},\vec{p}) = constant \qquad (5.2.3)$$



For each implemented module a one-dimensional, time-depending generalization of a harmonic oscillator is assumed (*eq. 5.2.4*). A single attribute of the convective cell determines the rate of change in the inertial part (pseudo-kinetic energy) as well as the quadratic terms appearing in the interaction part of the equation (potential field).

$$H(q,p,t) = p^2/2m - A * f(t)q^2 \qquad (5.2.4)$$

where *A* is a positive constant, *m* is the mass of the object inertia and *f(t)* is the correlation function between the object attribute evolution and the external field. For the COALITION model it is heuristically assumed that the total energy remains constant over time and equal to zero (5.*2.5*).

$$H(q,p,t) = 0 \qquad (5.2.5)$$

This assumption is based on the intuitive expectation that losses and gains of the pseudo-kinetic energy relate and are balanced by an exchange of energy with the surrounding environment. One of the main goals in developing our model was to convert heuristic relations between object evolution and its surrounding environments into forecast rules. A model for the energy conservation has been assumed and verified by means of a number of different functions representing the pseudo-potential energy. The function providing the best estimation scores was eventually selected as the best one to be implemented in the model. Under the aforementioned energy-conservation assumption, equation *(5.2.4)* can be solved analytically providing the following two solutions:

$$q(t)/q(t_0) = \sqrt{\exp \int_{t_0}^{t} \pm\sqrt{8A/m * f(t)}d\tau} \qquad with\ q(t), q(t_0) > 0 \qquad (5.2.6)$$

Each object attribute is described as a set of k-values corresponding to k pixels within the confined object. The distribution of the attribute through all pixels provides information about the variability of the attribute within the object. Equation *(5.2.6)* can therefore be generalized as

$$q^k(t)/q^k(t_0) = \sqrt{\exp \int_{t_0}^{t} \pm\sqrt{8A/m * f(t)}d\tau} \qquad with\ q^k(t), q^k(t_0) > 0 \qquad (5.2.7)$$

This allows for each convective cell to provide an ensemble forecast (see *Section 5.3 Working example*). The COALITION model forecasts the evolution of selected attributes of convective cells detected in its early stage and that are likely to further develop. In the current version of the model, only the cells development is taken into account and decaying processes are not considered. As a consequence only the positive solution *(5.2.8)*, which represents the forward propagator of our model and allows to forecast increases of thunderstorm intensities, is taken into account:

$$q^k(t) = q^k(t_0) * \exp\ \{\, 2/3 * \frac{\sqrt{2A/mB}}{B} * \left[{f_0}^k + B(t-t_0)^{\frac{3}{2}} - {f_0}^{\frac{3}{2}} \right] \} \qquad (5.2.8)$$

where

$$f(t) = {f_0}^k + B(t-t_0)^{3/2} - {f_0}^{3/2} \qquad (5.2.9)$$

$$f_0^k = 1/2 * [\dot{q}^k(t_0)/q^k(t_0)]^2 \qquad (5.2.10)$$

$$B = df/dt + df_{err}/dt = df/dt + \partial f_{err}/\partial\sigma * (\partial\sigma/\partial t) \qquad (5.2.11)$$

The potential field is built up on the values of the surrounding environment and steers the evolution of the object attribute, taking account of energy conservation (Hamilton). The characteristics of the external environment ($\partial\sigma$) are included in the model *(5.2.11)* and are used to explain the differences between extrapolated *(5.2.9)* and observed *(5.2.10)* f (*fig.4*). We exploit the correlation between averaged values of difference of f ($<f_{err}>$) and averaged values of environmental characteristics σ ($<\sigma>$).
This correlation, which takes into account regressive information, is used to forecast f for the following time-step.

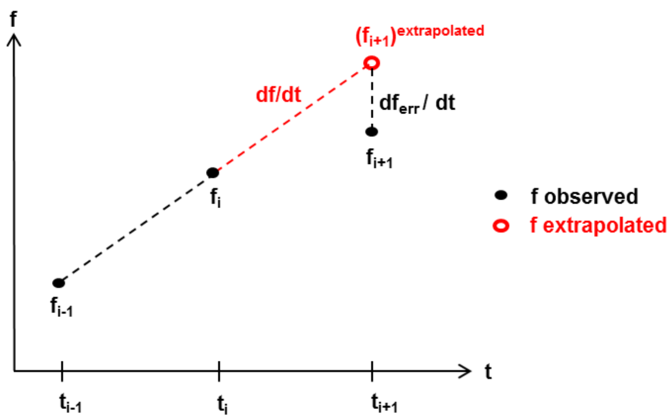


Figure 4. The model correlates the differences between extrapolated and observed f with the characteristic of the surrounding environment. This correlation is then used to forecast the f for the next time step (eq. 5.2.9).

5.3 Working example

This section provides additional information on the methodology of COALITION by means of an example that corresponds to module number two of the current version of the algorithm, where a satellite product is combined with a radar product. Let us select VIL as the attribute of the convective cells to be forecasted (i.e. used as generalized coordinate). The potential field V(CTT(t)) is then built as a distribution function of the environment characteristics controlling the development of the VIL, by taking into account the energy conservation (Hamilton).

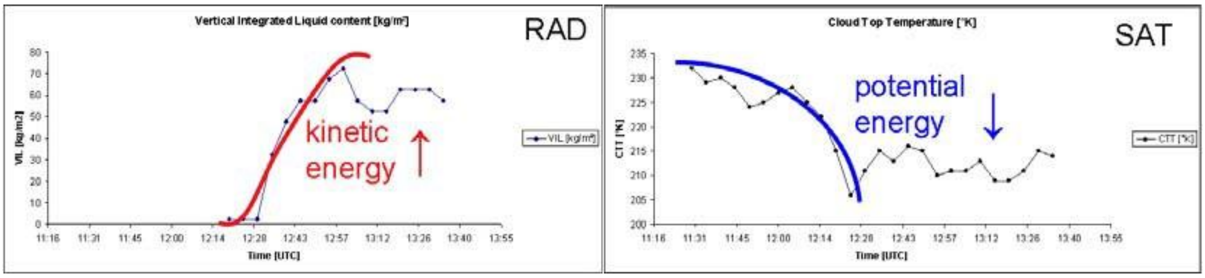


Figure 5. In the COALITION module 2 the pseudo-kinetic energy is estimated from a radar product (VIL) and the pseudo-potential energy is given by a satellite product (CTT). Energy losses or gains in the kinetic component are explained as an exchange of energy with the surrounding environment.

If the inertial state (kinetic energy) is assumed to be conserved, usual inertial rules of closed systems can be applied. This mostly happens in case of mature convective processes, for which nowcasting algorithms based on Lagrangian persistence are suitable. For all other cases, where such conservation is violated (in particular at initiation and early development stage), the system may no longer be considered to be closed. Energy losses and gains are then explained as import or export of energy from the surrounding environment through dynamical interactions (*fig. 5*).

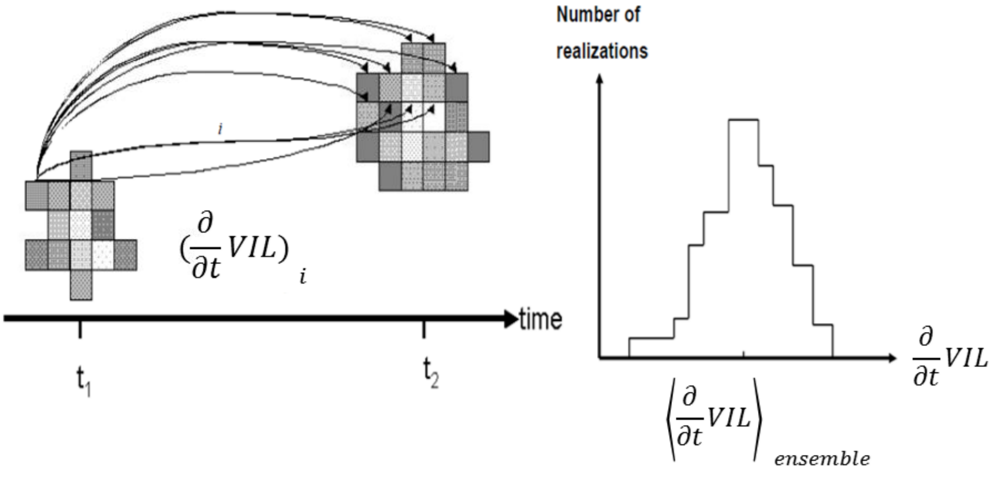


Figure 6. Assuming statistical stationarity, the kinetic energy is calculated according to the (discrete) rate of change of the object attribute (in this example the VIL). It is estimated for each possible realization i within the same thunderstorm cell (object) for two following time steps. On the right panel, the corresponding histogram is shown.

As described in *Section 5.2*, a one-dimensional harmonic oscillator is assumed: the VIL is used as generalized coordinate, i.e. it appears as quadratic form in the interaction term (potential field) and as quadratic form of its rate of change in the inertial part. The kinetic energy is calculated for each object portion using the VIL pixel value and taking into account all possible realizations. Figure 7a shows the evolution of kinetic energy expressed in percentiles for a 2-hour time-interval (12:00 - 14:00 UTC, 12.07.2010). Three time windows are selected at different convection phases. Time intervals identified with **A** show an increase of the kinetic energy. Let the VIL be the objects attribute, then the observed trend indicates that during these time intervals the thunderstorm is increasing its intensity (intensification of the precipitation). Changes in the slope of these percentiles give second order indications about acceleration and deceleration processes. Time intervals identified with **B** indicate that the thunderstorm is almost stable (i.e. neither evolution nor decaying of the convective cell). The last highlighted time interval **C** shows an energy decrease that can be interpreted as a clue of a decaying processes taking place and/or an homogenization of the VIL pixels distribution.
The correlation between kinetic energy and the CTT function ($g(t) = CTT_{50\%} - CTT_{25\%}$, where the $CTT_{50\%}$ value represents the median over the thunderstorm cell and $CTT_{25\%}$ the 25-percentile, see *fig. 7b*) is introduced in the Hamiltonian equation. The heuristic rule applied in this module can be summarized in: the larger the difference between the median and 25-percentile temperature (cloud expansion), the more energy is available for increasing the vertically integrated liquid (*fig. 7a*). By using *eq. 5.2.8* we obtain the forward propagator which allows forecasting the evolution of the object attributes, in our case the VIL.

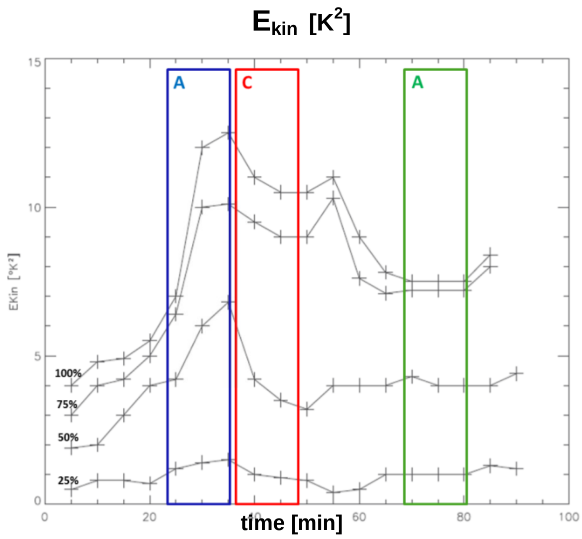


Figure 7a. Evolution of the vertical component of the kinetic energy over a 2 hours period (12:00 and 14:00 UTC on 12 July 2010); a percentile representation is used and units (K^2) are arbitrary but consistent with the simplified model; highlighted are time intervals A, B, C (see text).

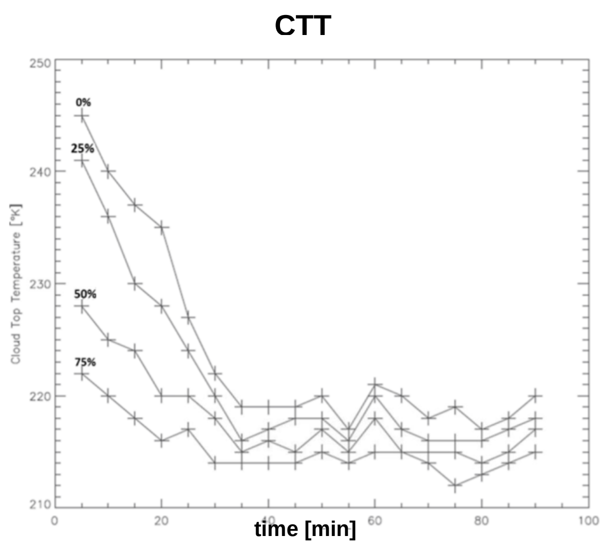


Figure 7b. Cloud top temperature distribution of the same convective cell represented in fig. 7a. The larger the difference between the median and 25-percentile temperature (cloud expansion), the more energy is available for increasing the VIL.

5.4 Algorithm structure

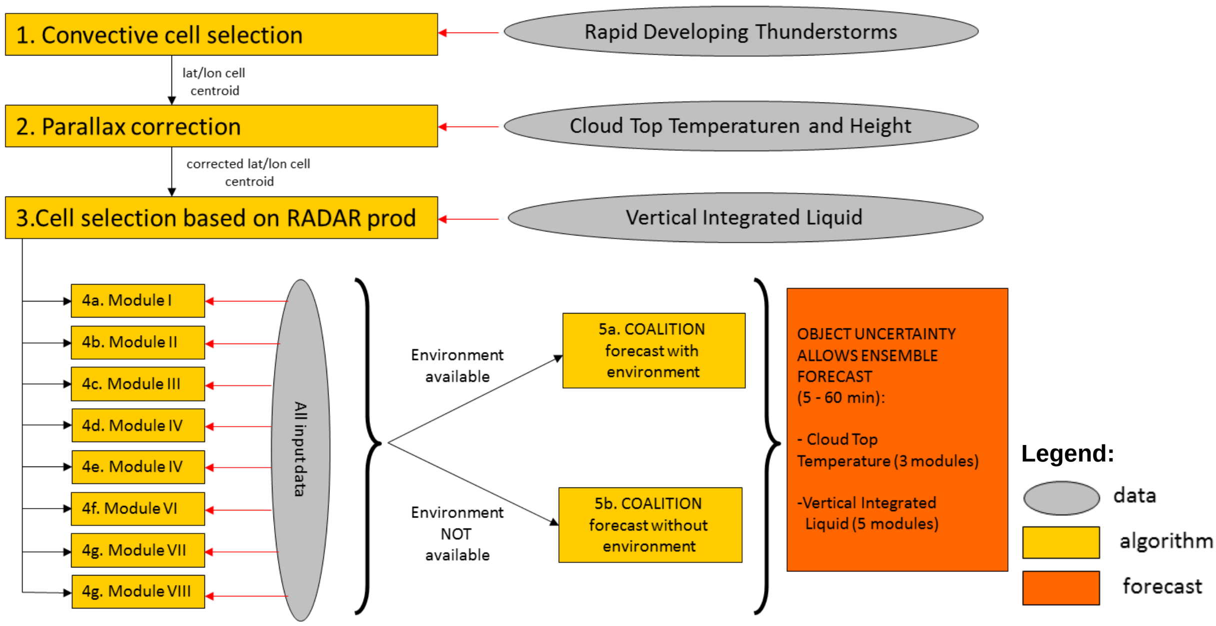


Figure 8. Flow chart of the COALITION algorithm, version 1. Summarized are the main steps of the data processing.

The algorithm uses as a preliminary input the Nowcasting SAF / Rapid Developing Thunderstorm (RDT) product. In order to detect small convective clouds, some of the thresholds in the RDT configuration file have been modified and verified. Based on this external information, COALITION selects and confines convective cells on MSG 10.8 µm infrared images. The region of interest can be defined by the user, in our case the alpine area. Once a convective cell is detected, the corresponding parallax correction is computed and applied. This step is very important in order to avoid georeferencing errors on the variety of products considered by the algorithm (radar data, environmental information provided by NWP outputs, climatological analysis or digital elevation models). The satellite and radar attributes of convective cells are then merged with external environment data (*Section 5.1, fig. 2*). If for one or more modules the needed data are missing, COALITION automatically takes the previous available information or it skips the concerned module, depending on the typical variability of the missing data. For example, if the environmental information CAPE (Convective Available Potential Energy) is not available, the previous value is taken (it could be the value from 5, 10 or 15 minutes before); as a matter of fact, this product does not vary considerably over a short time and small regions. However, if the missing product is the VIL, the modules requiring this input data are automatically excluded from the model, being the VIL a highly variable parameter over the time.
Taking into account the object uncertainties (*fig. 6*) each module provides two kinds of ensemble forecasts. The first forecast includes information about the surrounding environment. In the case the environment information is missing, then the ensemble forecast is based only on the evolution of the object's attribute during the previous time steps. At current status, COALITION relies on eight modules: three of them provide a forecast of the CTT, the remaining five a forecast of the VIL for 60 minutes with a time resolution of 5 minutes.

6 Results

6.1 Modules comparison

In this section forecasts provided by the eight modules for four randomly selected convective cells are presented. Two of them (case 2 and case 27, depicted in the upper panels of *fig.9*) developed into severe thunderstorms, the remaining two (case 16 and case 19) developed into a weak thunderstorm. The TRT ranking (Hering et al. 2004), which is operationally used at MeteoSwiss, is taken as a reference for assessing the storm severity.

Fig. 9 shows a comparison of COALITION's VIL forecast provided by different modules (modules 2, 3, 4, 5, 7; represented by different colors) for lead times between 5 and 60 minutes. The vertical green line refers to the VIL observation at the reference time. For the severe ones, the forecast reference is represented by the VIL value observed when the thunderstorm cell was firstly recognized as severe by TRT. For the weak ones, the forecast reference is given by the time when maximal observed VIL value is observed considering the whole life cycle of the cell.

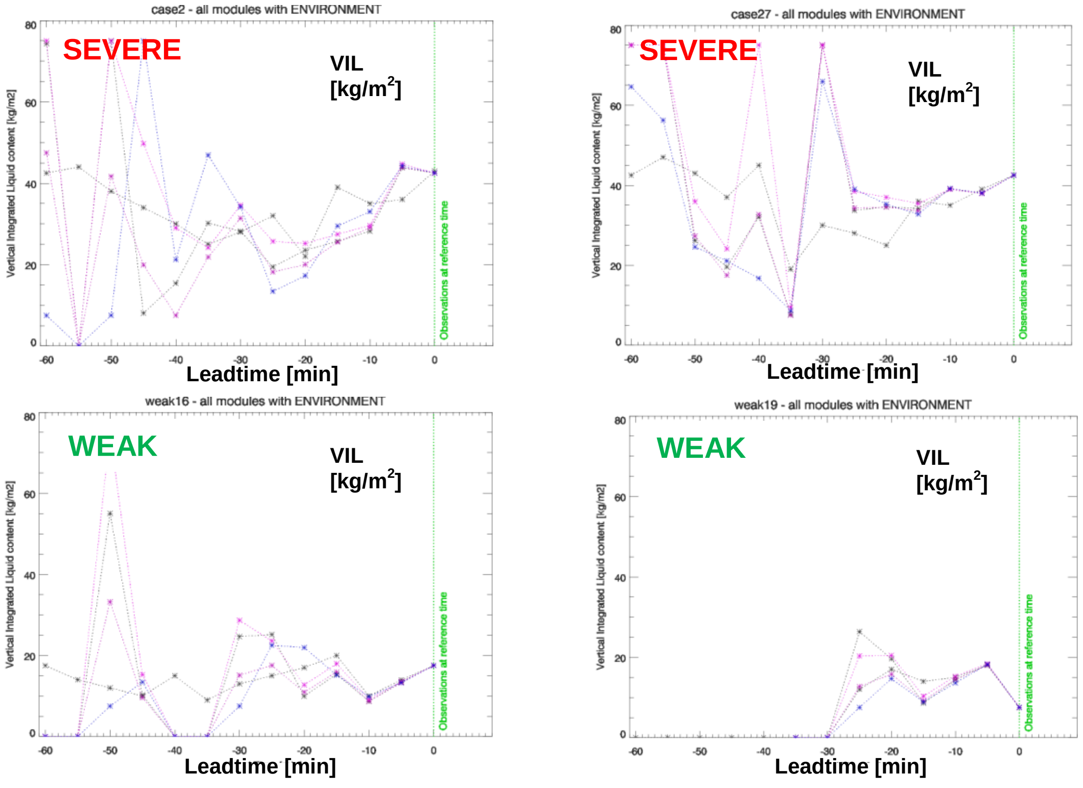


Figure 9.: forecasted VIL for four different thunderstorm cells (two severe and two weak). In the plots four colors are used to highlight the forecast provided by different modules (mod 2; mod 3 mod 4; mod 5; mod 7)

As expected, the differences between the forecasts increase with the forecast lead time. Deviations are a consequence of the different influence of the external environment on the object attribute: it can be that some environments support the development of severe convection, whereas at the same time other environments inhibit it.

Averaging the results of the analysis of 80 different cells, the forecast of severe storms generally shows a good skill up to 20 minutes before reaching the mature stage (RMSE < 8 kg/m^2). Explosive cells constitute an exception, since for this kind of storms the useful forecast lead time is reduced to 5-10 minutes. The main difficulty is associated with the handling of large increases of VIL: in some cases it can increase from 0 to 60 kg/m2 in less than 10 minutes. Although the environments show favorable conditions for severe convection, it is very difficult to forecast this kind of extremely rapid increases in the cell attributes. Regarding the VIL forecast for weak thunderstorms, the forecast skill remains good for longer lead times, in general up to 25-30 minutes (RMSE < 8 kg/m^2 at 30 minutes lead time). In these cases, most of the surrounding environments show less favorable conditions for the development of severe cells, and therefore the variability in the modules are smaller.

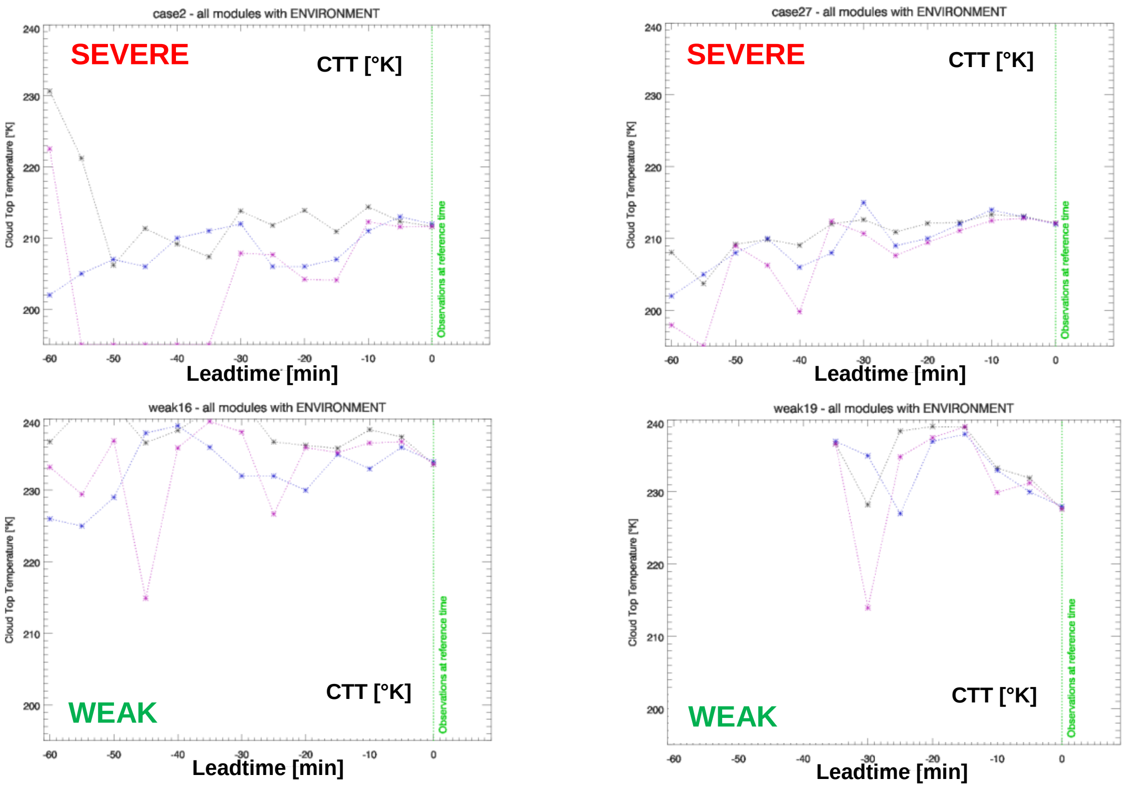


Figure 10. CTT forecasts for four different thunderstorm cells (two severe and two weak). In the plots two colors are used to show the forecast provided by different modules (mod1; mod 6; mod 8).

Fig. 10 shows the comparison of COALITION CTT forecasts provided by different modules (modules 1, 6, 8; represented with colors) for lead times between 5 and 60 minutes. The same thunderstorms as in *fig.9* are considered. The forecast reference has been defined using similar criteria as described above. For the severe thunderstorms, the forecast reference corresponds to the CTT value observed at the moment the thunderstorm cell was first recognized as severe by TRT. For the weak ones, the forecast reference is given by the CTT observed at the time when the maximal VIL value (considering the whole life cycle of the cell) has been observed. Generally, for both weak and severe convective cases, the CTT forecast provided by the three modules shows a good skill for long lead times, in some cases up to 30-50 minutes (RMSE < 8 °K at 40 minutes lead time). To better understand this skill, the variability of the thunderstorm's CTT and VIL shall be analyzed. As demonstrated by the analysis of the life cycle of a large number of convective cells, the distribution of CTT values remains more constant compared to the distribution of VIL values. This property, together with the fact that the CTT attribute is less variable in time compared to the VIL attribute, reflects in an improved forecast performance of the modules forecasting the CTT. As discussed in *Section 6.2* the good skill of the CTT forecast over longer lead times is contrasted by a higher FAR: in fact, the VIL attribute is more robust and reliable for discriminating severe thunderstorm cells from the weak ones.

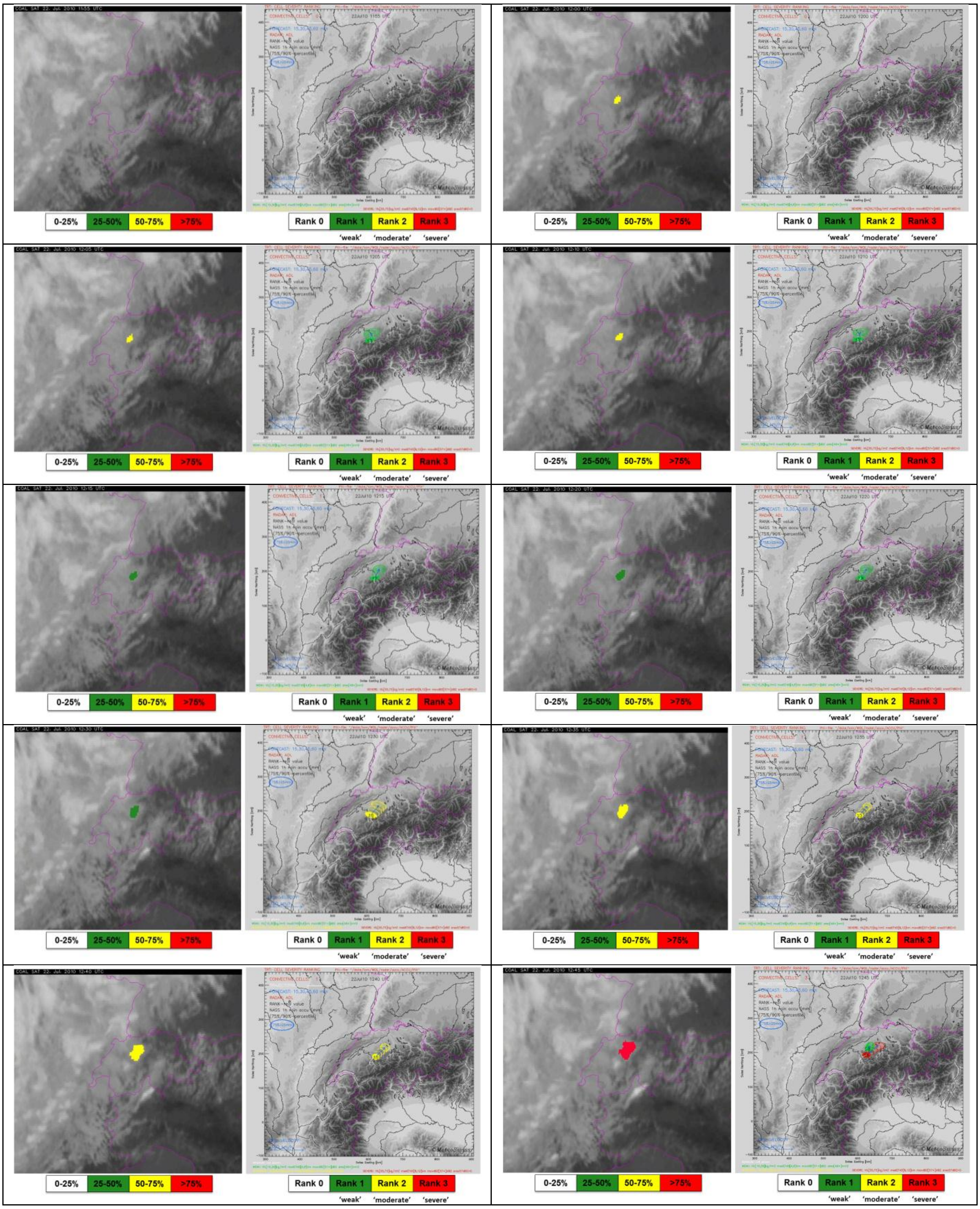


Figure 11. COALITION object-based probability map, showing the possible increase of the thunderstorm intensity in the following 15 minutes (first and third column) and thunderstorm detection and ranking by TRT (second and fourth column). The output of the radar nowcasting algorithm is taken as independent reference. Swiss alpine area,12.07.2010, 1155-1240 UTC.

The forecasts provided by the eight modules are combined together to assess the probability of a single convective cell to develop into severe thunderstorm within the following ten minutes. Examples of this object based probability are shown in the 10-panel view (*fig.* 11). A convective event over the Swiss alpine area on 12.07.2010 between 11:55 and 12:40 UTC is presented. At present, a single linear combination is used to merge all COALITION module forecasts, the following results are therefore to be considered preliminary results. A more refined combination of the forecasts is being developed, this will take into account the thunderstorm stage and the results of the preliminary validation (see *Section 6.2 First validation* and *7.0 Outlook*).

The case depicted in *fig. 11* shows a typical pre-frontal situation over the Swiss Alps. A south westerly flow precedes an approaching cold front and causes some prefrontal convective developments (visible on the infrared image provided by MSG), but, as confirmed by the COALITION and TRT, during the considered period just one convective cell has developed to a severe thunderstorm (see in the center of the images). This situation is usually very favorable for the development of well-structured and long lasting severe thunderstorms, crossing the northern part of Switzerland along the pre-alpine region. Such storms very often produce hail, strong wind gusts and, depending on their velocity and extension, large amounts of rain, increasing the danger of flash floods, especially in the valleys. Sometimes such cells show supercell features.

The COALITION outputs probabilities in four different classes and colors (*fig. 11*). For the considered case, at 12:00 UTC COALITION indicates the detected cell to have a probability between 50% and 75% to become severe within the next 15 minutes. This information is confirmed even in the next forecast and therefore can be considered to be robust. As shown in the reference (TRT), the considered storm cell was firstly detected at 12:05 UTC and classified as a weak thunderstorm until 12:20 UTC. During this period, the thunderstorm cell did not show any significant increase of intensity. This is confirmed by the analysis of the surrounding environment included in COALITION: most of the environmental parameters did not show favorable conditions supporting further developments. At 12:25 UTC the cell started an intensification process and at 12:40 was classified as severe.

The analysis of 80 different thunderstorm cells with different intensities demonstrated that for the cases where COALITION provides a probability greater than 25% for more than three consecutive time steps, the probability to increase its intensity and to reach the severe stage is very high. Therefore, when interpreting the output of COALITION, it is recommended not to take into account just the provided probability , but also to consider the continuity in time of this information. In addition to an improved combination of ensemble forecasts provided by different modules, it is planned to include the time evolution of the probabilistic information in the next version of the algorithm.

6.2 Preliminary validation

In this section, the preliminary validation of the eight implemented modules is described. The information provided by the TRT is taken as truth. For the development of the algorithm ten different thunderstorm have been selected (five of them were tagged as severe by TRT, the remaining ones as weak). 80 randomly selected thunderstorms (40 recognized as weak and 40 as severe) have been considered for the preliminary cross validation of COALITION modules 1-4,6-7. In the present validation the modules which use the CAPE as an external environment (modules 5 and 8) have been considered only six different cells . In the near future additional cases will be considered in order to improve the assessment of the forecast skills for modules 5 and 8.
As presented in *Section* 6.1 for cells classified as severe, the forecast reference is represented by the VIL and the CTT value observed exactly at the time when the thunderstorm cell was first recognized as severe by TRT. For the weak ones the forecast reference is represented by the maximal observed VIL and the corresponding CTT value observed at the same time, considering the whole life cycle of the cell.
For this preliminary validation, the convective cells are simply split into two groups (weak and severe thunderstorms). A thunderstorm is considered as severe if the maximal VIL value is greater than 35 kg/m^2 and the lowest observed CTT is colder than 225 °K; this criterion is based on forecaster's experience and on the thresholds used by TRT

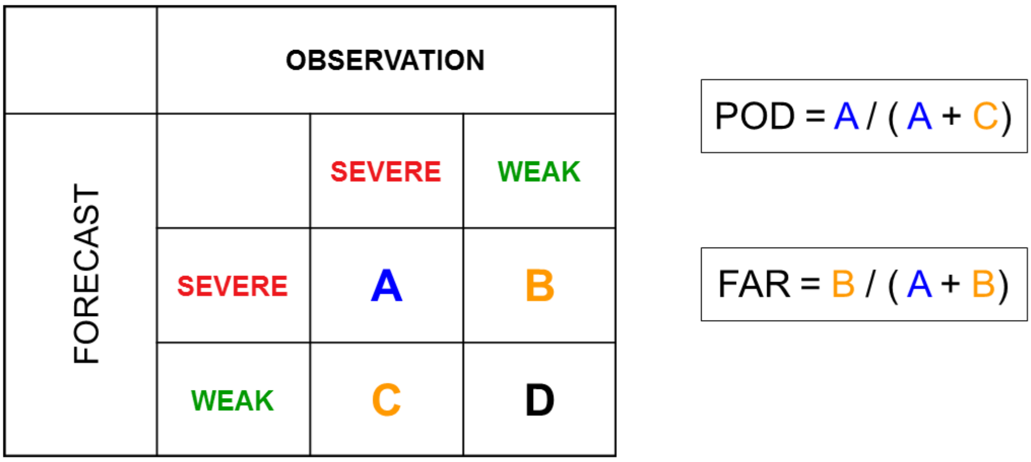


Figure 12. Scheme for assessing the probability of detection (POD) and the false alarm rate (FAR).

Fig. 13 shows the validation results for the five modules providing VIL forecasts. POD and FAR (*fig. 12*) are estimated for different times. For lead times until 20 minutes prior the severe stage, PODs for modules 2-4 and 7 ranged between 76% and 59%. The corresponding FARs show values between 12% and 34%. The module forecasts present slightly different results, which have to be explained by the differences in the involved external environment. It would be interesting to analyze these differences not only depending on their maximal observed VIL values, but also considering the synoptic conditions, the duration and the extension of the grouped cells. For example, by analyzing many cases it has been verified that for isolated, thermal thunderstorms the Convection Initiation product (included in modules number 1 and 4) provides more reliable information than in case of thunderstorm cells embedded in cold fronts. Therefore, it is expected that the corresponding modules show different skills depending on synoptic conditions.

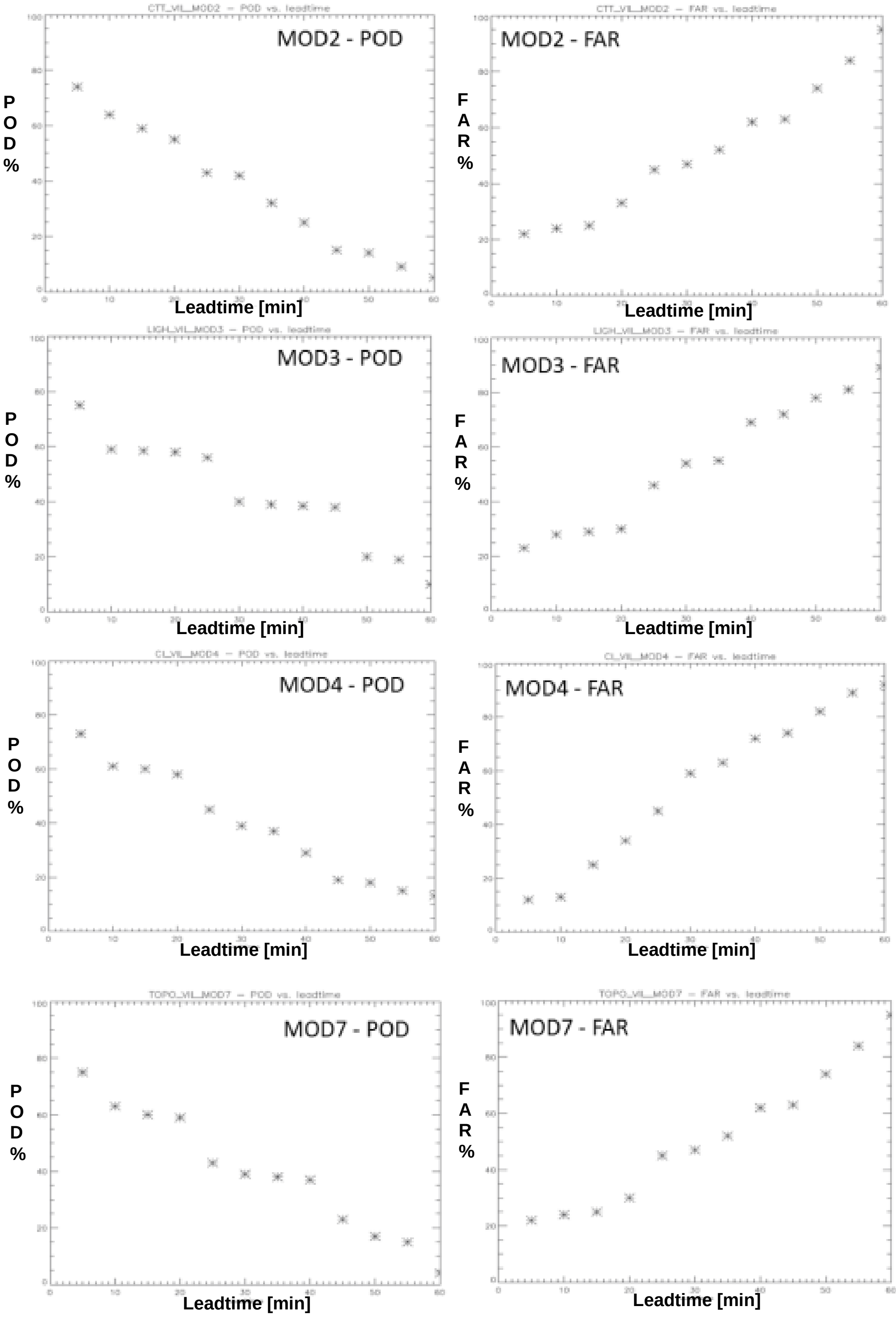


Fig 13. Preliminary validation of COALITION forecasts provided by modules 2 to5 and 7. Convective cells are classified in two groups, namely weak and severe convective cells. Cells are classified as severe and therefore used for assessing POD if the VIL exceeds 35 kg/m^2. For VIL values beneath this threshold, the cells are considered as weak and therefore they are used to assess the FAR. For modules number 2 to 4 and 7 the validation is based on 80 randomly selected cases, for the newly implemented module 5, however, only six cases are taken into account.

Other aspects, like the thunderstorm stage, are also very important. Some environmental information is only reliable during the initial cell development . When it reaches the mature stage, however, this information has a lower quality, due to many factors. A typical example is the cloud top temperature distribution: very often the attenuation caused by cirrus shields distorts the detected distribution of the temperature and, as a consequence, also the cloud morphology.
The presented results achieved by COALITION show a good skill, considering that it is a fully automated nowcasting system. For such systems, the end users (weather forecasters) require a POD over 60% and a FAR below 40%. Considering the present results, COALITION forecasts should be usually considered as reliable only for following 20 minutes.
The scores obtained involving the CAPE show higher values for both PODs and FARs. We have to remember that for this modules only six casas are considered, so that the results cannot be compared to the other ones.

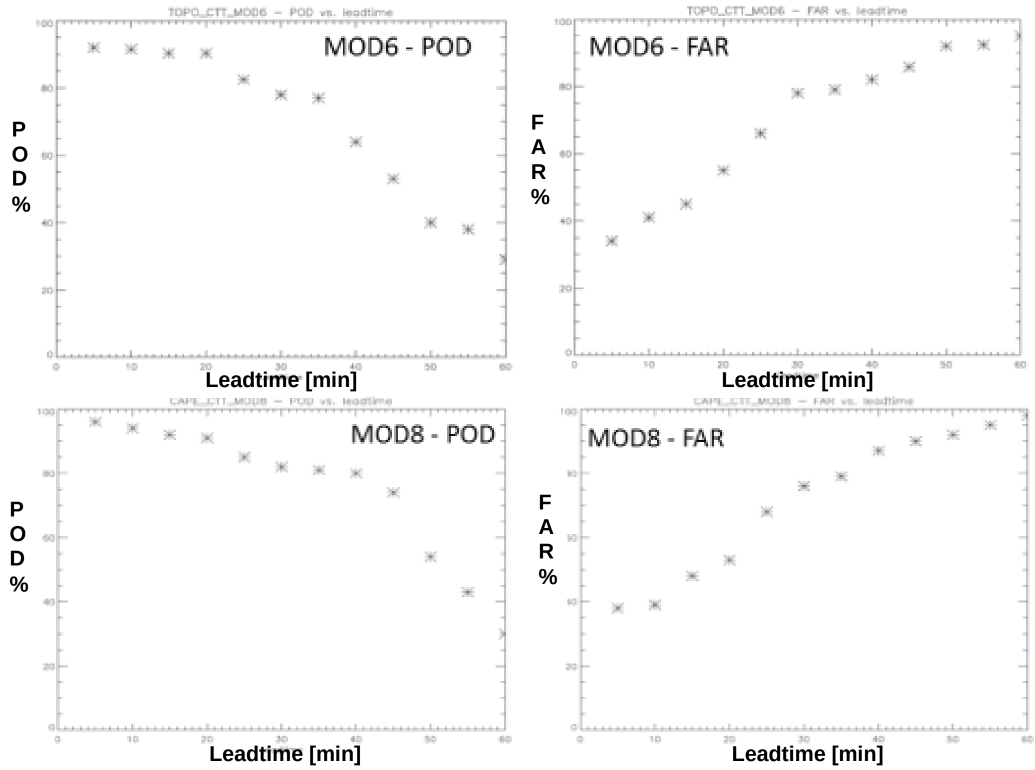


Figure 14. Same as Figure 13, but for modules 1,6 and 8. Convective cells are classified into two groups, namely weak and severe convective cells. Cells are classified as severe and therefore used for assessing POD if the minimal CTT is colder than 225 °K. For warmer CTT, the cells are considered as weak and therefore used to assess the FAR. For modules number 1 and 6 the validation is based on 80 randomly selected cases, for the newly implemented module number 5, however, only six cases are taken into account.
Fig. 14 shows the validation results for the three modules providing CTT forecasts. High PODs, but also larger false alarm rate compared to the other modules. In fact, it is more difficult to discriminate severe from weak thunderstorm cells based on CTT than VIL. Even weak thunderstorm cells can often reach very cold CTT of about 215 °K. This first consideration indicates that the VIL parameter is more robust and reliable for assessing the intensity of thunderstorms. The three modules providing CTT forecasts can be very useful when considered in the early stages of a convective cell, when the cloud top star but the radar does not yet detect any precipitation.
These are only preliminary assessments: the ongoing work includes the use of the forecast uncertainty and the combination of different modules (optimized weighted combination, fuzzy logic) for assessing more rigorously the forecast skill in order to provide the best probabilistic information about the development of convection intensity as early as possible.

Diagrams in *fig. 15* show a first global validation of the algorithm, where the module's results are merged by a simple linear combination. During the first 20 minutes lead time, the POD decreases from 79% to 60%, whereas the FAR increases from 26% to 39%. These first results could already be considered as useful for automatic nowcasting of heavy thunderstorms. Forecasts for lead times longer than 20 minutes, however the skill decreases often rapidly.

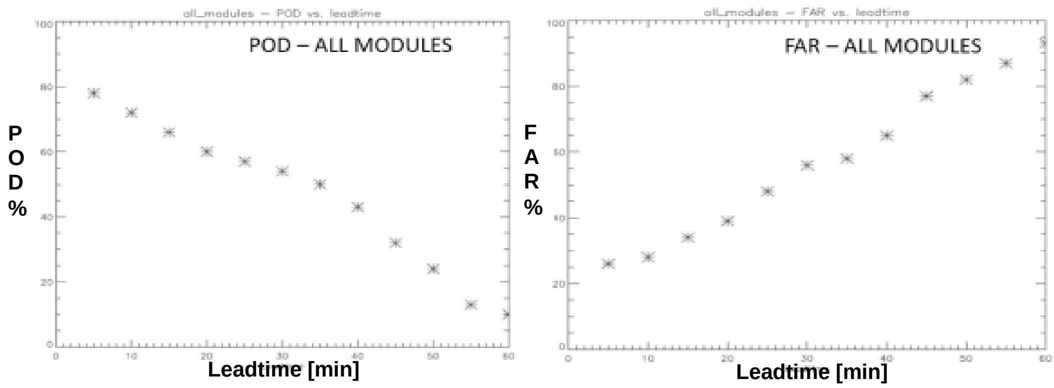


Figure 15. Global validation of the COALITION algorithm, where the module's forecasts are merged using a simple linear combination. Classification of the thunderstorm is the same as described in captions of fig. 13 and 14.

6.3 Conclusions and outlook

This report presented a newly developed nowcasting approach (COALITION) to forecast severe convective storms by assimilating data from different sources and combining them by means of a conceptual model. The current version of the algorithm implements eight modules merging thunderstorm attributes with information of surrounding environments. Using TRT as an independent reference, a preliminary cross validation has been carried out on 80 randomly selected cases for lead-times ranging from 5 to 60 minutes. Quantitative analysis of object attribute forecasts and the related skill scores obtained by analyzing a large number of thunderstorm cells shows promising results.
The validation results demonstrate that COALITION's 5 to 20 minutes nowcast is a usually reliable tool for weather forecasters. COALITION detects convective cells which are likely to increase their intensity with a POD higher than 60% and a FAR lower than 40%. The COALITION's concept and methodology is therefore suitable for short time nowcasts. As described in *Chapter 6,* COALITION's underlying idea is to explain cell's energy losses and gains with energy exchanges with the surrounding environment, according to the assumed total energy conservation rule. This interaction is described as a dynamical process. The fact that module results become unstable after 30-40 minutes (values diverge considerably) gives an indication that this methodology cannot be used for long term forecasting. The first version of the model has been developed and is going to be tested in real-time during the convective season 2012. Forecasters' feedback will be collected and considered for the tuning of the algorithm.
COALITION is an easily configurable system and it allows multiple extensions. All further developments concerning the algorithm as well as the ingested data can be considered and summarized in a first category of improvements. The system has been developed and tuned particularly for the early stage of convective (development phase). One of the main goals is to include other data types (in particular additional environmental data) in order to improve the algorithm's skill to forecast cells regeneration and decaying. High priority will be given to the low level moisture convergence , a crucial parameter in long lasting thunderstorms and

for reintensification processes (Pucillo et al., 2009). Other relevant predictors as wind shear, potential vorticity and even additional synoptic parameters could be included, depending on the morphology of the target area. For what concerns the decaying processes,
the dissipation term in the Hamiltonian equation has to be considered (*Chapter* 5). During the development phases of a cell this term is neglected because is considered to be very small compared the other terms. This assumption is confirmed by the fact that the total energy of the object-environment system remains constant over the time. However during the mature stage of a cell, this term becomes more and more important, since the total energy is no long conserved.

Another category of improvements concerns the graphical post-processing of the model results. As described in this document, probability maps are at the moment provided by linearly combining the results of the modules. The analysis of the variability in the results from various modules, together with the information about different convection stages, could contribute to a further improvement of the global forecast capability. The modules including satellite based information about the cell (e.g. distribution of cloud top temperature field, Convection Initiation) are expected to provide better and more reliable forecasts for the early development stage. Approaching the mature stage, the modules including information provided by radars should have higher weight in the forecast.

Last but not least, an improved statistics over the ensemble will increase the COALITION's skill. Object uncertainty (used for providing the module ensemble forecasts) represents a crucial information to be used also for assessing more rigorously the probability of a cell to increase its intensity.

Another improvement should be applied to the methodology used to summarize the probabilistic information into one single map in order to simplify its interpretation. Currently, four different probability classes are provided and displayed with different colors. As demonstrated by the validation results, additional information about the reliability of the probabilistic forecasts can be gained by considering a time series of the predicted probability instead of single values. The persistence of a predicted probability over 25% during several successive time steps indicates a slightly higher likelihood for the forecast to be correct. The information about the frequency should therefore be automatically included in the system.

The actual version of the COALITION will be tested in real-time during summer 2012 and deployed at MeteoSwiss by the end of 2012. The same model can be run in both real-time and offline mode (for reprocessing purposes): this feature will be very useful in order to implement new feature, test them and finally run them in real-time mode. A second improved version of COALITION including new modules and fine-tuned configurations is planned; the new version will also provide an improved graphical post-processing.

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Appendix A

Between May 2009 and June 2012 the EUMETSAT Fellowship project COALITION has been presented in following conferences, workshops and seminars:

- Embry-Riddle Aeronautical University (Arizona) Summer School in Mountain Meteorology (Locarno, 19th June 2012)
- EUMETSAT/CIMSS Remote Sensing Seminar (Sasso Di Castalda, 12-18th July 2009)
- 2nd Convection Working Group Workshop (Landshut, 08-10th October 2009)
- EUMETSAT Fellow Day 2009 (Darmstadt, 10th December 2009)
- MeteoSwiss Radar and Satellite Team Science Day 2010-1 (Locarno-Monti, 23th February 2010)
- University of Bern, Institute Applied Physics (IAP) Seminar (Bern, 23th April 2010)
- 10th EMS Annual Meeting (Zürich, 13th - 17th September 2010)
- EUMETSAT Meteorological Satellite Conference 2010 (Cordoba, 20th - 24th September 2010)
- EUMETSAT Fellow Day 2010 (Darmstadt, 8th December 2010)
- MeteoSwiss Radar and Satellite Team Science Day 2011-1 (Locarno-Monti, 22th February 2011)
- National Center of Atmospheric Research (NCAR), short term scientific mission (Boulder 19th Mai – 2nd June 2011)
- EUMETSAT Meteorological Satellite Conference 2011 (Oslo, 5th - 9th September 2011)
- Meeting “Amici della Meteorologia”, (Bellinzona, 22th September 2011)
- MeteoSwiss Radar and Satellite Team Meeting (Locarno 30th September 2011)
- COALITION presentation at General Direction of MeteoSwiss (Zürich, 17th October 2011)
- ECSS2011, European Conference on severe Storms (Palma De Mallorca, 3th – 7th October 2011)
- EUMETSAT Fellow Day 2011 (Darmstadt, December 2011)
- University of Bern, Seminar at the Institute of Geography (Bern, 13th March 2012)
- 3rd Convection Working Group Workshop (Prague, 27th-30th March 2012)

During the second semester of 2012 is planned to present the COALITION project in following seminars/conferences/schools:

- EUMETSAT Meteorological Satellite Conference 2012 (Sopot, 3th - 7th September 2011)
- Swiss Geoscience Meeting 2012 (Bern, 16th – 17th November 2012)

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